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Thin films of ferroelectric crystals

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Thin films of ferroelectric crystals

The invention relates to a method for the production of thin film of non linear optical ferroelectric crystals in accordance with the preamble of claim 1 and relates to a thin film of non linear optical ferroelectric crystals according to the preamble of claim 5 as well as to various applications of thin films.

The invention generally relates to applications of thin films of ferroelectric materials in integrated optical devices for telecommunication and data communication. The thin films of ferroelectric materials can also be used in applications such as electronic memory devices, pyroelectric detectors and piezoelectric actuators. In particular the invention relates to fabrication of thin films of nonlinear optical materials and integrated optical devices for amplification and switching of light-wave signals.

Description of prior art

Owing to large frequency-bandwidth of optical fibers, light-wave technology provides the ability to send a large amount of data using a very small fiber. To maximize the transmission capability of optical fibers one has to use wavelength division multiplexing (WDM) technology. The current long-haul communication systems use WDM technology for transmitting large amount of data over optical fibers.

To build an optical communication system using WDM technology one requires to generate, amplify, modulate, filter and detect optical signals with different wavelengths. To generate optical signals one needs to be able to amplify the optical signals. To modulate the optical signal one requires changing the refractive index of the material and using some optical circuit to modulate optical signals. To filter the WDM signals one need to use optical filters and finally one needs detectors for this purpose.

Generally these functions are performed with different technologies in optical communication systems. For example for generation semiconductor devices are used, for amplification erbium doped fiber amplifiers (EDFA) are used. For modulation $LiNbO_3$ Mach-Zehnder modulators are used. To filter the signals Glass planner waveguide circuits are used. Finally for detection different semiconductors are used.

Since different technologies and materials are used, the WDM optical communication systems are usually very expensive and require a large space.

It is the general object of this invention to fabricate thin films of nonlinear optical crystals for the fabrication of nonlinear optical devices to be used for generation, modulation, amplification and filtering of light-wave signals.

It is another object of the present invention to introduce new devices, which can be made using the thin films of optical nonlinear materials for amplification, modulation, filtering of lightwave signals.

It is a still further objective of the present invention to provide applications for the proposed devices and the introduction of optical communication systems that can be made using the proposed technology.

The present invention therefore addresses the problem of the fabrication and the application of a material system in order to allow a significant reduction of the size of integrated optical devices for telecommunication and data transmission.

This problem is solved by the measures specified in claim 1 and 5.

Advantageous configurations and applications of the invention are specified in further claims.

In this invention a technology is provided, which meets all the required functions in a single material system except for detection, which can be done using normal detectors. Also using this technology it is possible to reduce the size of optical devices 100 to 1000 times smaller. Since the size is reduced and all the required functions are made in a single material system the price of the system can be reduced significantly.

Since the WDM communication system can be made in a very compact way it is also possible to use the system for data communication. The speed of the computers are now limited to the speed of the communication of signals between different modules in a computer. Using the described technology it is possible to use light-wave signals inside a computer to transmit the data much faster than printed circuit boards currently used.

The technology introduced is based on the fabrication of thin films of optical materials with large nonlinear coefficients. The fabricated thin films can also be used for memory devices, pyroelectric devices and piezoelectric actuators.

Owing to large nonlinear coefficient for ferroelectric crystals such as $LiNbO_3$ and $LiTaO_3$ and $KNbO_3$ are desirable to fabricate thin films with high quality for integrated optical devices. For the fabrication of thin films several methods have been used in the past. Molecular beam epitaxy, plasma sputtering, Laser pulse deposition and some other methods have been used in the past. However the thin films obtained by these methods have two main problems. First the films can be grown on special substrates, which provide lattice matching to the crystal. This will limit the fabrication process to very few cases and one cannot achieve optical wave-

guides with desirable properties. Second the quality of the fabricated films is not as good as bulk crystals. The optical losses are very high and the electro-optic coefficient is very small. A good method for the fabrication of thin films of nonlinear crystals with high quality does not exist.

The current devices based on the nonlinear crystals use bulk crystals and they form a low index contrast waveguide in the crystal by ion exchange or diffusion to form an optical waveguides. Switching of the light is achieved in these devices by changing the refractive index of the material by applying an electric field to the waveguide. Also optical amplification is achieved by use of three wave mixing in these crystals. To achieve phase matching periodic poling is used. The devices for switching and modulation are very big (up to 2cm long) and the devices for amplification have very small bandwidth.

In this disclosure a method is described for the fabrication of thin films of nonlinear crystals as well as new devices, which can be made for amplification, modulation and filtering of the light-wave signals using the thin films that are made.

Detailed description of preferred embodiments

The invention will become apparent upon consideration of the following detailed description of specific embodiments thereof with a reference to a drawing in which:

Fig. 1 The fabrication process for preparation of thin films of $LiNbO_3$ on SiO_2 cladding layers;

Fig. 2 Microscope image for the fabricated $LiNbO_3$ waveguide;

Fig. 3 multi-layer waveguide fabricated by repeating the fabrication process invented with crystals with different spontaneous polarization direction vector;

Fig. 4 a multi-layer $LiNbO_3$ waveguide with modulated nonlinear susceptibility direction;

Fig. 5 Chromatic dispersion calculated for bulk crystal of $LiNbO_3$ and the calculated chromatic dispersion for different waveguide configuration. The chromatic dispersion can be forced to zero at the 1.55mm wavelength by careful choice of the refractive index of the cladding of the waveguide;

Fig. 6 Calculated gain spectrum for parametric amplification for different cladding index for $TM_0^{\omega} \rightarrow TM_2^{2\omega}$ conversion for different refractive index of cladding for a $LiNbO_3$ waveguide;

Fig. 7 a Mach-Zehnder modulator structure;

Fig. 8 a micro-ring modulator (switch) structure with coupling waveguides;

Fig. 9 the modulation (switching) of light by shifting the resonance wavelength in an electro-optic micro-resonator;

Fig. 10 a Mach-Zehnder modulator with electro-optic micro-ring resonators coupled to different arms;

Fig. 11 the transmission of the micro-ring coupled Mach-Zehnder structure for different values of the phase difference induced by shifting the resonance wavelengths of the micro-resonators;

Fig. 12 a multi-wavelength modulator (Switch), which uses several micro-resonators with different resonance wavelength;

Fig. 13 a wavelength router, which can route any input wavelength in any input port to any, output port;

Fig. 14 a high order filter realized by coupling micro-resonators with different coupling coefficients to different arms of a Mach-Zehnder switch;

Fig. 15 the electrode structure for coupling the light of the micro-ring structure for inducing losses in the micro-resonator structure;

Fig. 16 the calculated losses for periodic modulation of refractive index in a micro-resonator as a function of number of periods of electrodes

A first general embodiment of the present invention is shown in Fig. 1. This figure shows the basic procedure, which is used for the fabrication of thin films of nonlinear optical crystals. As is shown in Fig. 1, first a $LiNbO_3$ crystal is ion implanted using ionized He+ atoms. The He+ atoms are accelerated in an electric filed and are used to bombard the nonlinear crystal. The energy for these ions varies between 100keV to 1Mev and this energy determines the final thickness for the thin film fabricated using this method. Because the He+ ions penetrate into the crystal, a damaged layer is formed inside the crystal. In this layer the bonding between the adjacent atoms is broken due to the presence of the He atom.

A layer of SiO_2 is deposited on another $LiNbO_3$ sample using plasma enhanced chemical vapor deposition system. This layer will behave as a buffer layer or a cladding for the optical waveguide, which will be fabricated. The thickness of this layer can be between a few nano-meters to 2-3 micrometers. The thickness of this layer must be optimized according to the thickness of the core layer to minimize the coupling of the light to the $LiNbO_3$ substrate. A thin film polishing technique is developed to smoothen the surface of the deposited SiO_2 layer.

The ion implanted sample and the sample with cladding layer are bonded together using standard wafer bonding techniques. To achieve this, the samples are cleaned using the organic solvents and using RCA1 solution activates their surface. The samples are brought into contact inside de-ionized water and are pressed against each other to form a bond between them. The samples will attach to each other after this process. Next the bonded samples are heat treated to increase the bonding strength. The samples are placed in an oven at 180ºC

for 10 hours for this purpose. By increasing the temperature further to 600ºC, a thin layer of crystal is split and transferred to another substrate. Hence one will obtain a thin layer of the nonlinear crystal using this method. Fig. 2 shows the picture of thin film of $LiNbO_3$ crystal, which has been made using the described technique. Since the thin film is directly fabricated from a bulk nonlinear crystal it has the optical properties of a bulk crystal. Hence the optical losses are very small and the electro-optic coefficient is very high.

Notice that by repeating the method described above with crystal with different directions for spontaneous polarization vector, one can make structures as shown in Fig 3. This type of structure is very useful for nonlinear optical wave mixing.

In order to demonstrate how this embodiment achieves all the objectives of the present invention, it is necessary to consider new devices, which can be made using these thin films.

First we consider optical amplification and generation. To achieve an optical amplifier in a nonlinear optical crystal one has to convert a photon from a strong optical pump signal through nonlinear interaction into two-photons, one in the signal wavelength and one in the idler wavelength. The optical signal frequency of the pump and the signal and idler obey the following energy conservation equation:

$$\omega_p = \omega_i + \omega_s \tag{1}$$

To achieve a practical amplifier one need to have the phase matching condition. The phase matching is given by:

$$n(\omega_p)\omega_p = n(\omega_s)\omega_s + n(\omega_i)\omega_i \tag{2}$$

It is the subject of this invention to introduce a new method to achieve phase matching. This method employs the matching of effective index of the waveguide to achieve phase matching between the guided modes. Basically one needs to match the

effective index of different guided modes in a nonlinear crystal waveguide. However since the refractive index of the material increases with the frequency ω it is only possible to match modes with different orders. Hence the overlap integral for mode conversion:

$$S=\int d_{i,j,k}(x,y)E_m^{(2\omega)}(x,y)(E_n^{(\omega)}(x,y))^2\,dxdy \qquad (3)$$

where E is the electric field for the guided mode and $d_{i,j,k}$ is the nonlinear susceptibility and x and y are the Cartesian coordinates, is normally small or zero. One technique to achieve large S is to change the sign of the nonlinear susceptibility coefficient d in equation (3) so that the overlap integral is maximized. To achieve this one requires to change the sign of the d coefficient where the mode sign for $E^{(2\omega)}$ changes. Hence the optimal structure will look like what is shown in Fig 4 to maximize the S for phase matching the fundamental TM mode at ω to the second mode of second harmonic TM mode at 2ω using e.g. d_{33} of $LiNbO_3$ in a 3D waveguide. Notice that this type of waveguide can be made by using the thin film fabrication method described above and normal lithography. Notice that S has the unit of 1/length (excluding d and assuming normalized E). So $1/S^2$ can be considered as an equivalent effective area for the mode. In this case we can simply use all the formulas for nonlinear processes for bulk crystal and replace the area by an effective area $1/S^2$.

Consider the structure shown in Fig. 4. The dimensions of the structure are chosen such that the phase matching is achieved for the conversion at the wavelength of 1.55μm. Using a mode solver program the modes for this structure are calculated and the overlap integral S is calculated for the $\chi^{(2)}$ inverted case. The effective area for conversion is obtained to be approximately 2μm×2μm and the effective nonlinearity for $TM_0^{\omega}\rightarrow TM_2^{2\omega}$ is calculated to be as high as η=3000%/Wcm^2 for d_{33} of $LiNbO_3$ at 1.55μm. It is obvious at this point that this structure is highly efficient in SHG since the optical mode

power is confined to a very small area and the overlap integral between the modes is very large.

The gain coefficient for parametric amplifier is given by:

$$G=\frac{1}{4}\exp(2\sqrt{\eta P_{pump}}L) \qquad (4)$$

where η is the second harmonic conversion efficiency, L is the length of the amplifier and P_{pump} is the pump power. Considering the efficiency calculated in previous section and assuming pump power of P_{pump}=300mW and L=1cm one can obtain G as high as 20dB. This value is high enough to be used as a practical amplifier.

Next we consider the functional dependence of the gain to the wavelength. Notice that in parametric amplification the required phase matching is written as:

$$n(\omega_p)\omega_p = n(\omega_s)\omega_s + n(\omega_i)\omega_i \qquad (5)$$

where p, s and i are pump, signal and idler frequency respectively. First consider that phase matching for this case can be achieved in the same way as second harmonic generation discussed before. So assuming fundamental modes for ω_i and ω_s and a higher order mode for ω_p one can find the right thickness to achieve phase matching. We can find this thickness by assuming that $\omega_i=\omega_s=\omega_p/2$. (since we are interested to generate the pump for parametric amplification using second harmonic generation this is a good choice). One can easily prove that if the effective refractive index is a linear function of the wavelength then equation (5) is also satisfied for all wavelengths.

Notice that the effective refractive index is a function of both the material dispersion and the waveguide dispersion. So in general the effective refractive index is a complicated function of the wavelength. One can approximate the effective index using the Taylor series expansion:

$$n(\lambda)=n(\lambda_0)+\frac{dn(\lambda)}{d\lambda}(\lambda-\lambda_0)+\frac{d^2n(\lambda)}{d\lambda^2}(\lambda-\lambda_0)^2+\ldots \qquad (6)$$

So if the second derivative of the effective refractive index with respect to wavelength is zero and higher order term are negligible then the effective index is a linear function of the wavelength and the phase matching condition will be achieved over a large wavelength range. Notice that this is identical to the condition of making the chromatic dispersion equal to zero in an optical fiber for high-speed transmission of signals:

$$D(\lambda)=-\frac{\lambda}{c}\frac{d^2n_e}{d\lambda^2}=0 \qquad (7)$$

where $D(\lambda)$ is the chromatic dispersion (CD). Normally in electro-optic crystals this condition is not satisfied for the material dispersion. Fig 5 shows CD as a function of the wavelength for $LiNbO_3$ crystal. As it can be seen this function is always negative in the visible and the infrared wavelengths of interest. It is therefore impossible to satisfy phase matching over a long wavelength range using crystal birefringence or periodic poling. However if one calculates the CD of a waveguide mode one will get wavelength regions, where CD is positive. Therefore these two effects can cancel each other and it is possible to achieve zero CD at a desired wavelength. This is again identical to shifting of the zero of chromatic dispersion by carefully designing the fiber. Notice that now we require two condition to be satisfied at the same time. First, one needs to satisfy the phase matching condition at a given wavelength and second, one needs the CD to go to zero. This can be achieved by changing both the refractive index of the cladding and the core thickness.

As an example consider the design of a parametric amplifier at 1.55µm using $LiNbO_3$. To design the right structure we obtain the right thickness, which satisfies the phase matching condition for each cladding refractive index. Next we calculate the dispersion. Table 1 summarizes the calculated waveguides thickness and cladding indices, which satisfy the

phase matching condition and no dispersion for slab and 3d waveguides of $LiNbO_3$. The dispersion can be forced to become zero at the wavelength of 1.55µm for TM slab waveguide and also for both TE and TM modes of 3d waveguides. However the dispersion cannot be forced to zero for the TE mode of a slab waveguide of $LiNbO_3$ for practical numbers for the refractive index of the cladding. Fig. 5 also shows the dispersion as a function of wavelength for $LiNbO_3$ bulk and for the designs in Table 1 as a function of wavelength. Notice that for 3D waveguides one has an extra degree of freedom for choosing the aspect ratio of the waveguide. This might be used for polarization independent phase matching. The amplification gain spectrum for the slab waveguide is plotted in Fig 6 for $TM_0^{\omega} \rightarrow TM_2^{2\omega}$ conversion for different refractive indices of the cladding. As it can be seen the gain spectrum is very wide (over 500nm). From this gain spectrum only the half with lower or higher frequencies than the pump wavelength could be used since besides the signal also the idler wave will be generated in parametric amplification. It is interesting to note that the maximum bandwidth is achieved when the cladding refractive index is slightly higher than in the case where dispersion is equal to zero. This comes at the expense of some ripples in the gain spectrum.

Table 1 shows the calculated thickness and refractive index of the cladding to achieve phase matching and zero chromatic dispersion for different conversion schemes:

	Core Thickness (μm)	Cladding refractive index	Width (3d) (μm)	Dispersion (fs/nm/cm)
Slab $TM_0^{\omega} \rightarrow TM_1^{2\omega}$	0.728	1.48	–	0
Slab $TM_0^{\omega} \rightarrow TM_2^{2\omega}$	2.045	1.6	–	0.027
	2.044	1.62	–	0
	2.042	1.64	–	-0.036
	2.041	1.66	–	-0.07
3d TM $TM_0^{\omega} \rightarrow TM_2^{2\omega}$	1.577	1.75	1.492	0
	1.415	1.66	1.092	0
3d TE $TE_0^{\omega} \rightarrow TE_2^{2\omega}$	1.275	1.66	1.067	0

Table 1

A second issue is the coupling the light to the structure. Notice that it is very difficult to excite the third mode of the waveguide. A better method can be to generate the pump by second harmonic generation. Notice that this is automatically achieved if phase matching condition is satisfied for the case in which $\omega_s = \omega_i$. This method has previously been demonstrated for periodically poled $LiNbO_3$ waveguides.

Notice that for this type of phase matching one requires a large refractive index difference between core and cladding. This has several advantages. First the waveguides are small. This means that the intensity will be larger for a given power and hence the parametric gain will be high. Secondly since the waveguides cores have a large refractive index difference compared with the cladding, one can make micron-sized bends. Spiral amplifiers for example can be realized for reduced size optical elements. Consider that the 1cm length waveguide can be made into a spiral with 500μm diameter for example. Thirdly one can change the width of the waveguides and achieve phase matching at different wavelengths. This means that in a single chip it is possible to

extend the amplification wavelength. Fourthly the noise figure of this type of amplifier is basically the quantum limited noise of 3dB in phase-insensitive modes and also the noise figure can be made equal to zero in phase-sensitive modes.

The thin films of nonlinear optical materials can also be used for the fabrication of optical switching devices and modulators. To achieve an optical switch one needs to use a nonlinear optical material in an optical circuit. Since the refractive index of the fabricated thin film is very high compared to the cladding layer, one can make very small bends. So one can make optical devices with sizes as small as a few micrometers. The following devices can be made using the thin films of nonlinear crystals for switching of light. The simplest device is a Mach-Zehnder device in which the refractive index of one arm is changed by applying a voltage to modulate or switch the light as shown in Fig. 7. In this device the refractive index of one arm changes and hence the phase of light will changes. By using a 3dB coupler one can achieve switching.

The next device, which can be made using the fabricated thin film, is an electro-optic micro-ring resonator as shown in Fig 8. In this device due to electro-optic effect the resonance wavelength changes and a selective wavelength is modulated or switched as shown in Fig. 9.

The next device is a wavelength selective switch in which two micro-resonators are coupled to two arms of a Mach-Zehnder modulator. Notice that the phase of the light changes close to the resonance wavelength of a micro-resonator in a single micro-resonator is coupled to a waveguide. Hence by making a structure as shown in Fig. 10 and by poling the micro-resonators in a push pull fashion one can modulate the transmitted light. By shifting the resonance wavelength of the micro-resonators in different direction the phase of the transmitted

light will change and similar to a Mach-Zehnder device the light will be switched. Notice that this is very similar to a Mach-Zehnder modulator however this structure is wavelength sensitive. The light wavelength must be close to the resonance wavelength of the resonator to achieve modulation. The transmission for this modulator as a function of wavelength for different values of phase difference induced by electro-optic effect is shown in Fig. 11.

Notice that in the micro-ring modulator the switching is achieved by shifting the resonance wavelength of the device. Hence if one wavelength is switched on the adjacent wavelength will switch off. However in the Mach-Zehnder based switches one can simply turn on a single wavelength or turn off the desired wavelength. This is very useful for the applications that we will discuss. Also the Mach Zehnder based device is 2 times more sensitive to the applied voltage if it is made in a push-pull fashion. Finally it is shown that any desired transfer function can be fabricated using two all pass filters in a Mach-Zehnder structure. Hence one can make higher order switches simply by adding more resonators coupled to the waveguide.

Many applications can be considered for the wavelength selective switches introduced. One can consider for example a multi-wavelength modulator as shown in Fig. 12. In this structure each pair of micro-rings is adjusted close to resonance at a given wavelength. Hence they will only modulate the desired wavelength and pass the rest unaffected. So it is possible to modulate different wavelengths in a small single chip. Using practical devices one can modulate up to 100 different wavelengths as speed of 10Gbit/sec. Hence it is possible to transfer about 1Tbit of data in a single waveguide to the optical signal. This can be used for computer interconnect for example.

Also one can consider the structure as a wavelength selective switch in which the desired wavelengths will be switched to the desired output channel. One can switch different wavelengths in a single device as shown in Fig 12. This can be used in wavelength routers as depicted in Fig 13. A wavelength router is a device in which it can route the optical signals of different wavelength from any input waveguide to any output waveguide. Using the optical circuit as shown in Fig 13 one can achieve this function. Using the fabricated thin films it is possible to make this wavelength router. Notice that the number of switching stages must be equal to the number of input waveguide so that one can switch from any input waveguide to any output waveguide.

Notice that the micro-resonator as described above is a wavelength selective filter. Also more complicated filters can be fabricated by coupling several micro-resonators to achieve lower cross talk between adjacent channels. These filters can be in the form of the device shown in Fig. 14. Notice that any desirable transfer function can be realized by the sum or difference of two all-pass filters. Using the device shown in Fig 14 and by carefully adjusting the coupling coefficient one can achieve a desirable transfer function for filtering applications.

Finally one can change the refractive index of the waveguide periodically and couple the light out of the waveguide made out of the described method. Fig 15 shows the device concept. An electro-optic micro-resonator is considered. A periodic field is created by applying a voltage to the electrodes of this device as shown in Fig 15. The periodic field induces a periodic index change in the core of the micro-resonator. This index change will couple the light out of the micro-resonator. This is similar to a grating coupler for a straight wave-guide. Notice that this grating is induced through an electro-optic effect. Hence one can induce the grating very rapidly. So it is possible to make an electro-

optic loss induced switch. One can use this effect to change the losses for micro-resonators. Also the introduction of losses is important for coupled cavity resonators. To achieve a precise transfer function for coupled cavity resonators one needs to achieve a precise resonance wavelength and precise coupling. The resonance wavelength can be easily tuned using electro-optic effect. However the coupling cannot be adjusted after the device is fabricated. However by introduction of losses into the cavity one can compensate for the inaccuracy in the coupling coefficients. By the method introduced in this invention one can tune both losses and resonance wavelength using electro-optic effect. This is very useful to achieve coupled cavity devices.

Using a perturbative method one can calculate the coupling between the guided modes and radiation modes in micro-ring resonators. Assuming that the perturbation due to index change is given by:

$$\delta n_{co}(r,\varphi)=\delta n\exp(im\varphi) \tag{8}$$

where n_{co} is the core index, m is the number of periods of electrodes and δn is the electro-optic index change. Also assuming the electric filed for guided mode is given by:

$$E_z(r,\varphi)=\Phi(r)e^{i\beta\varphi} \tag{9}$$

Where $\Phi(r)$ is the filed profile and β is an integer number for resonance modes, one can show that the radiated power is given by:

$$P_{rad}=\frac{1}{8}\sqrt{\frac{\varepsilon_0}{\mu_0}}k_0^3(2\pi)^2\left(\int_0^R J_{\beta-m}(-n_{cl}k_0r')(2n_{co}\delta n)\Phi(r')dr'\right)^2 \tag{10}$$

Where J is the Bessel function and n_{cl} is the cladding refractive index. Fig. 16 shows the calculated radiated power for a micro-resonator as a function of the number of periods for the electrodes m. The micro-resonator is assumed to have an outer diameter of 29μm, core index of 1.6, cladding index of 1.3 and the optical wavelength is equal to 1.55μm. The electro-optic coefficient is assumed to be 30pm/V. As it can

be seen from this figure for *m* very small the losses are limited by radiation losses. By increasing the *m* further the losses rapidly increase since the guided mode matches to the first radiation mode. By increasing *m* further the losses decrease since the overlap integral between the guided modes and radiation modes decreases. It is interesting to note that by applying 10V/µm it is possible to induce 2dB/cm loss. Notice that the losses increase as a square function of the index change. So by applying 20V/µm the losses are as high as 4dB/cm. This value is very high and can be used in practical electro-optic micro-resonator to make switches or to compensate for the in accuracy in the coupling in multi-cavity micro-ring resonators.

Notice that all the required functions in a multi-wavelength communication system are realized with this single technology. The generation, amplification, switching and modulation and filtering can be all realized using the described thin films.

List of abbreviations and acronyms

CD	Chromatic dispersion
EDFA	erbium doped fiber amplifiers
PECVD	Plasma enhanced chemical vapor deposition
RCA1	auch RCA-1, RCA 1: wafer cleaning solution
WDM	wavelength division multiplexing

Claims

1. Method for the production of a thin film of non linear optical ferroelectric crystals, where the thin film is formed by at least by two substrates of said non linear optical crystals,
characterised by the steps:
A deposition of a glass material using the PECVD-method on a first substrate;
B bonding another substrate with a damaged layer produced by ion implantation;
C heating to remove a thin layer of non linear optical crystals for making an index contrast waveguide of the glass material, which index is in the range of 0.4 till 0.7.

2. Method according to claim 1
characterised in by
the non linear optical crystals are $LiNbO_3$ or $KNbO_3$ or $LiTaO_3$.

3. Method according to claim 1 or 2,
characterised in by
in step A the refractive glass material is SiO_2.

4. Method according to any one to the claims 1 to 3,
characterised in by
repeating the steps A to C in order to obtain thin films of nonlinear optical crystals with different direction for the nonlinear susceptibility.

5. A thin film of non linear optical ferroelectric crystals, where the thin film is formed by at least by two substrates of said non linear optical crystals, characterised in by a first substrate contains glass material; another substrate contains a damaged layer, which is produced by ion implantation; where the index contrast waveguide of the glass material is in the range of 0.4 till 0.7.

6. A thin film according to claim 5 characterised in by the non linear optical crystals are $LiNbO_3$ or $KNbO_3$ or $LiTaO_3$.

7. A thin film according to claim 5 or 6, characterised in by that the refractive glass material is SiO_2.

8. A thin film according to any one of the claims 5 to 7, characterised in by repeating the steps A to C in order to obtain thin films of nonlinear optical crystals with different direction for the nonlinear susceptibility.

9. Use of a thin film according to any one of the claims 5 to 8 in an optical amplifier which uses the cladding refractive index to force the dispersion of a waveguide to zero to achieve wide-band parametric amplification.

10. Use of a thin film in an optical amplifier according to claim 9 in parametric oscillator.

11. Use of a thin film according to any one of the claims 5 to 8 in an A Mach-Zehnder modulator or switch.

12. Use of a thin film according to claim 11, where the Mach-Zehnder modulator is coupled with micro-ring resonator.

13. Use of a thin film according to claim 11 or 12 in Mach-Zehnder modulators building a dynamic wavelength router for routing optical signals of different wavelengths.

14. Use of a thin film according to any one of the claims 5 to 8 in a multi-wavelength modulator in which different wavelengths are modulated in a single chip using micro-ring structures containing the thin films.

15. Use of a thin film according to any one of the claims 6 to 8 in any device, which uses the piezoelectric effect of $LiNbO_3$.

16. Use of a thin film according to any one of the claims 6 to 8 in any device, which uses pyroelectric effect of $LiNbO_3$.

17. Use of a thin film according to any one of the claims 6 to 8 in any device, which has the functionality of a memory in electronic system.

Abstract

A new technique for the fabrication of thin films of ferroelectric crystal is introduced. The method can be used to make thin films of ferroelectric crystals with thickness varying from 0.1 µm to a few microns. The thin films of ferroelectric materials can be used for memories, piezoelectric actuators, pyroelectric sensors, MEMS devices and optical waveguides. The thin films can be fabricated on top of a low index material so that one can make optical waveguides with large index contrast between the core and cladding. The fabricated thin films can be used to make optical switches such as micro-ring resonator, optical amplifiers, optical filters and other integrated optical devices. A new optical amplifier using parametric process is introduced. The amplifier is built by using the invented thin film fabrication method. New optical integrated circuits based on the invented fabrication method are described.

Fig. 1

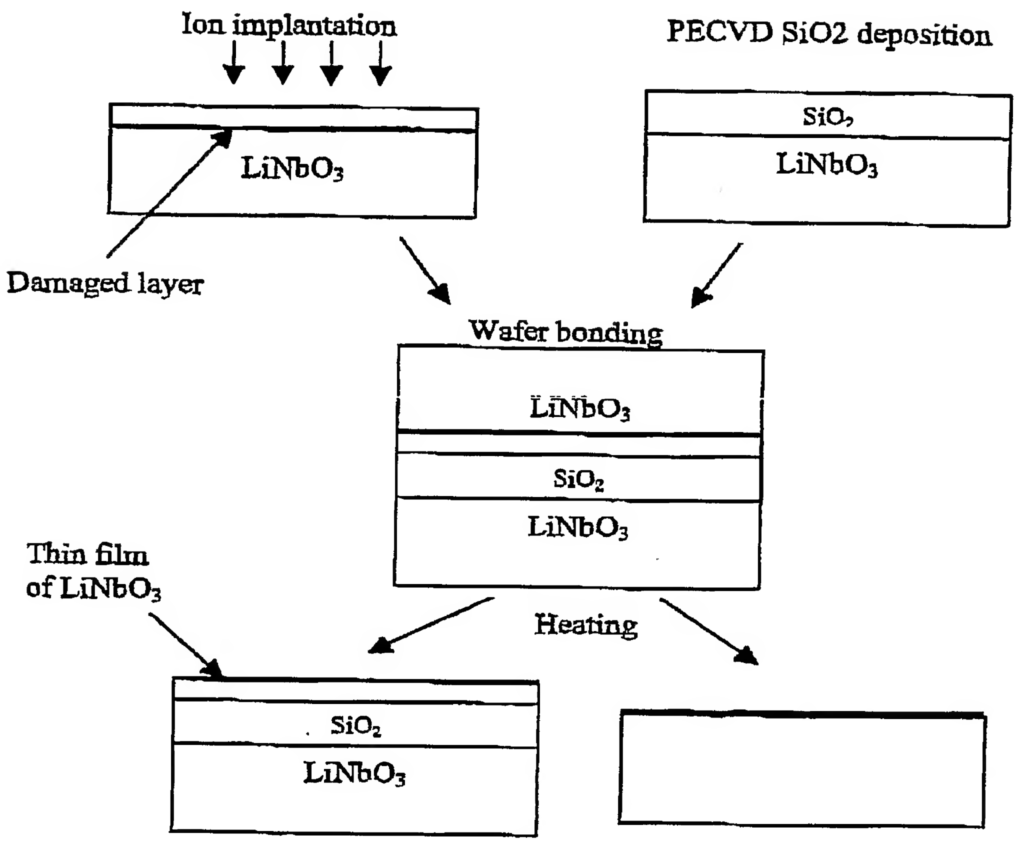
Ion implantation
PECVD SiO2 deposition
SiO_2
$LiNbO_3$
$LiNbO_3$
Damaged layer
Wafer bonding
$LiNbO_3$
SiO_2
$LiNbO_3$
Thin film
of $LiNbO_3$
Heating
SiO_2
$LiNbO_3$

Fig 1

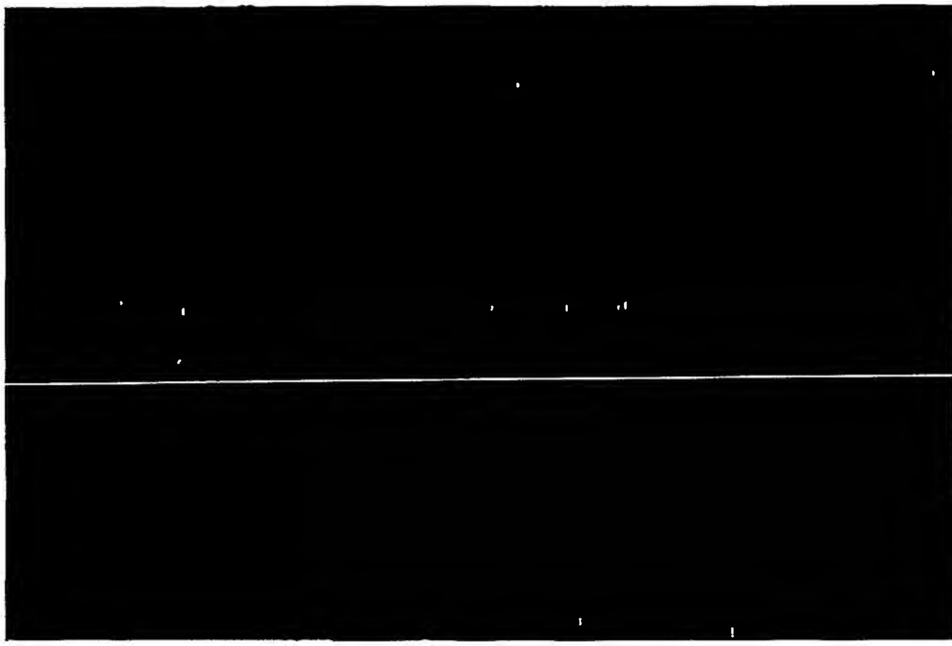

Fig. 2

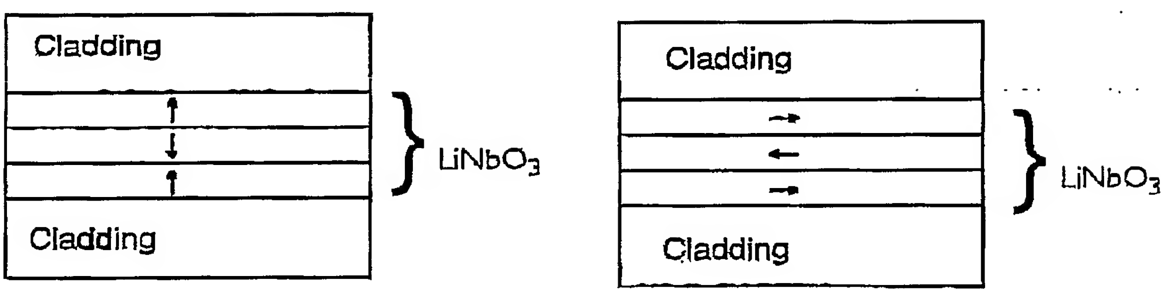

Fig 3

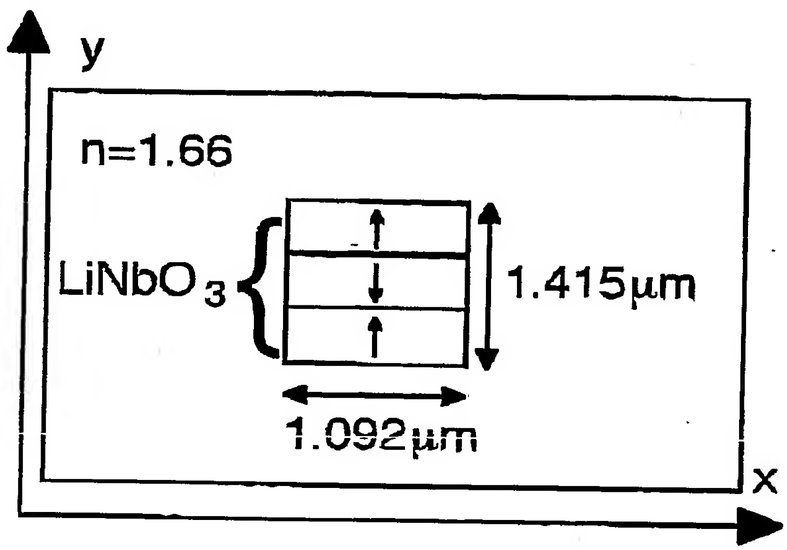
y
n=1.66
$LiNbO_3$
1.415μm
1.092μm
x

Fig 4

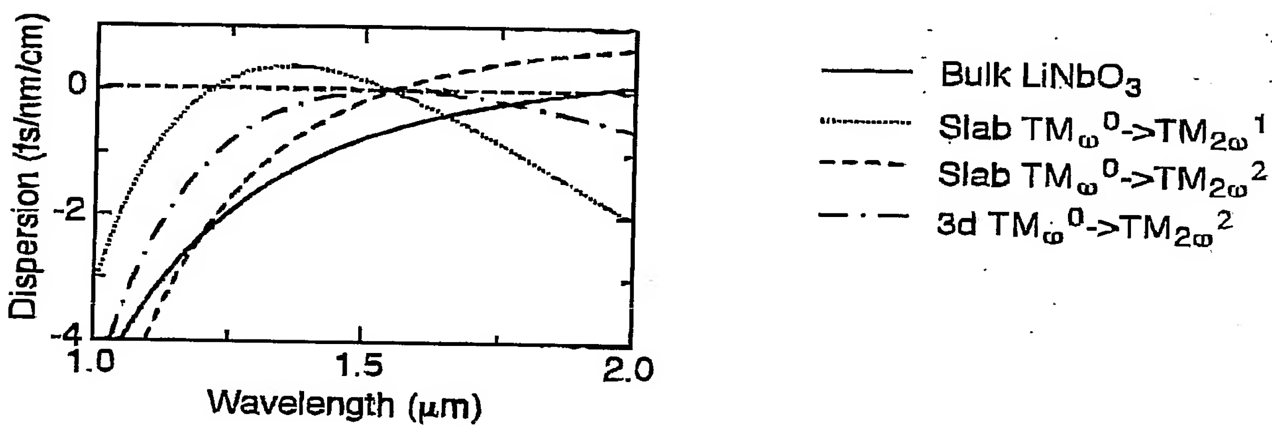
Dispersion (fs/nm/cm)
0
-2
-4
1.0
1.5
2.0
Wavelength (μm)
Bulk $LiNbO_3$
Slab $TM_\omega{}^0$->$TM_{2\omega}{}^1$
Slab $TM_\omega{}^0$->$TM_{2\omega}{}^2$
3d $TM_\omega{}^0$->$TM_{2\omega}{}^2$

Fig. 5

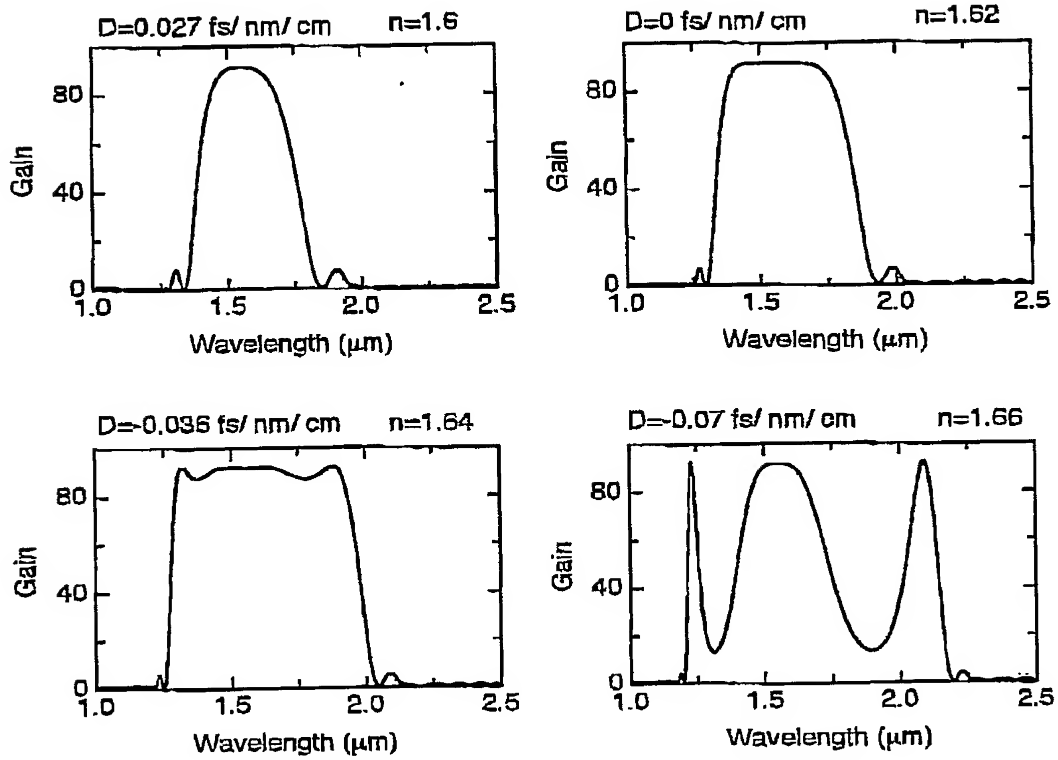
D=0.027 fs/ nm/ cm
n=1.6
Gain
Wavelength (μm)
D=0 fs/ nm/ cm
n=1.62
Gain
Wavelength (μm)
D=-0.036 fs/ nm/ cm
n=1.64
Gain
Wavelength (μm)
D=-0.07 fs/ nm/ cm
n=1.66
Gain
Wavelength (μm)

Fig 6

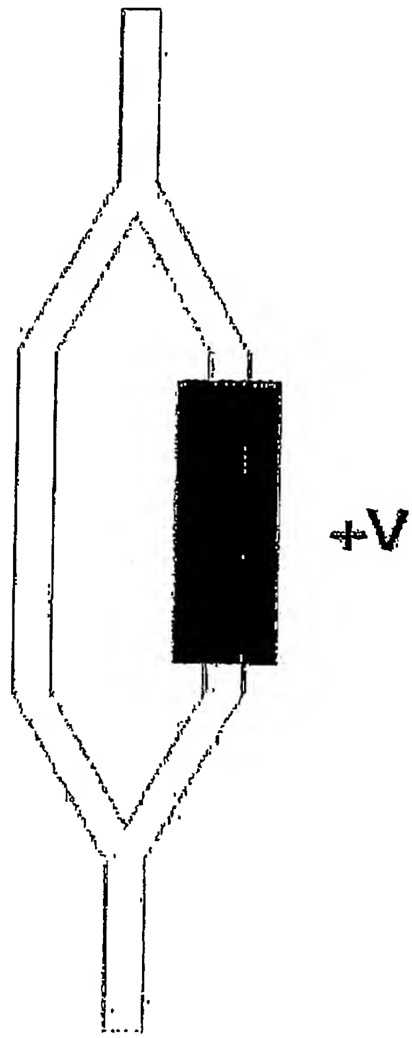

Fig. 7

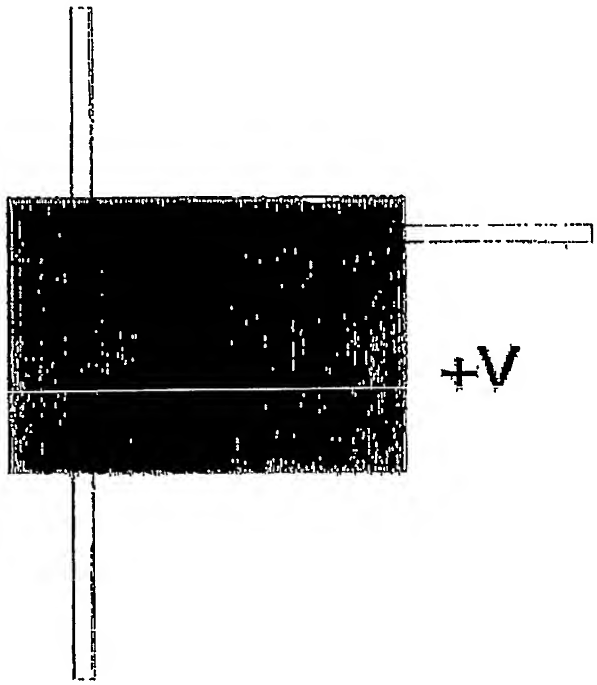

Fig. 8

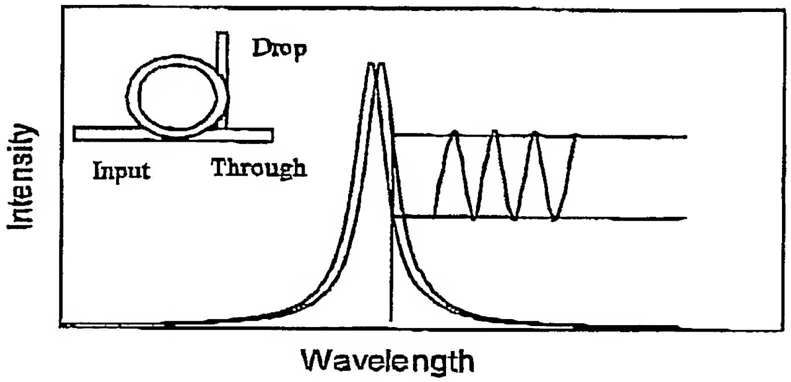

Fig. 9

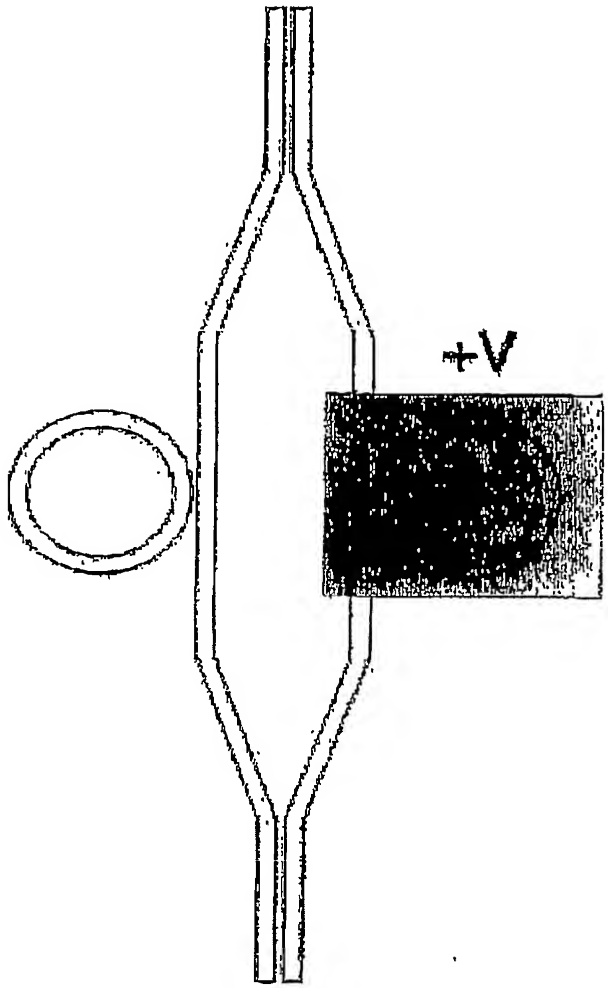

Fig. 10

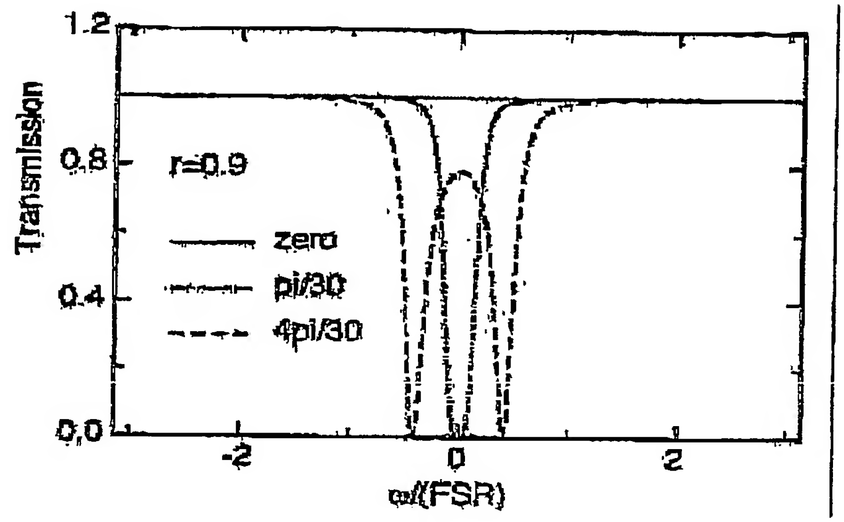

Fig. 11

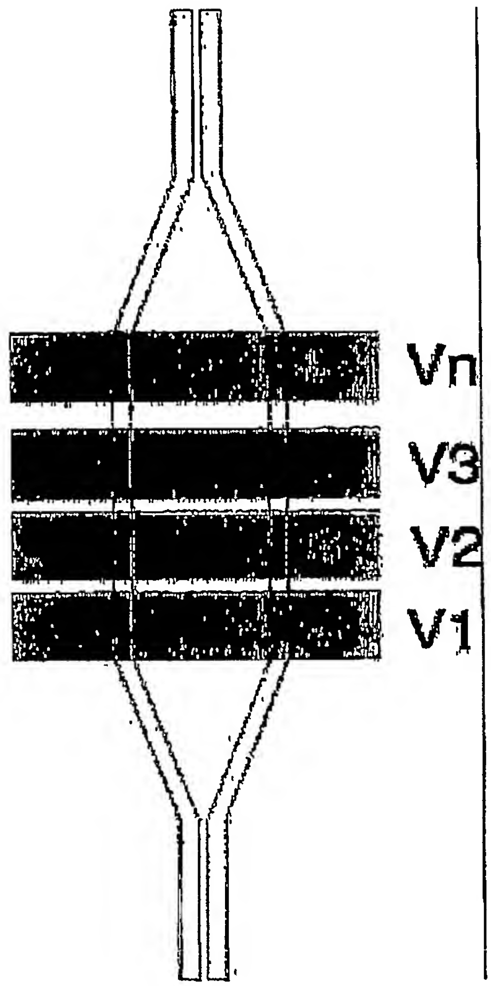

Fig. 12

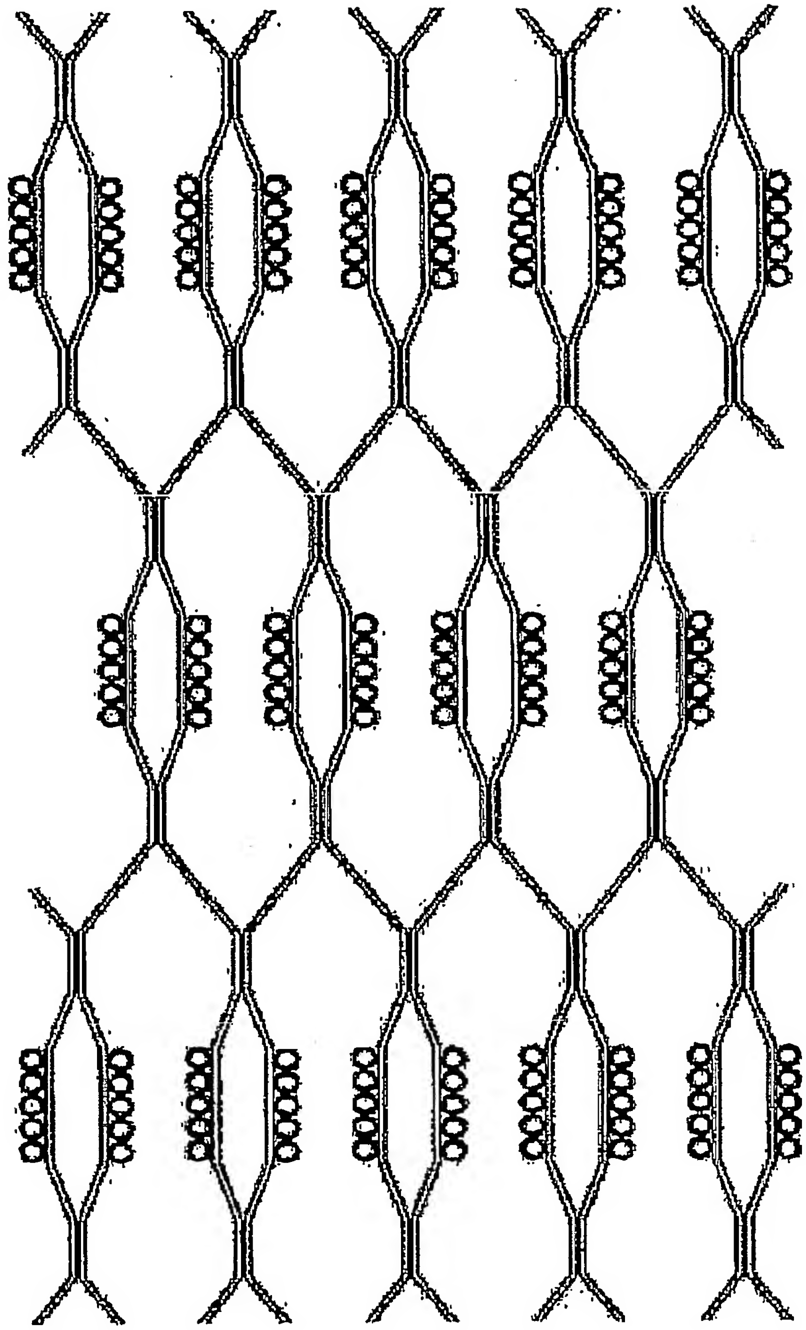

Fig. 13

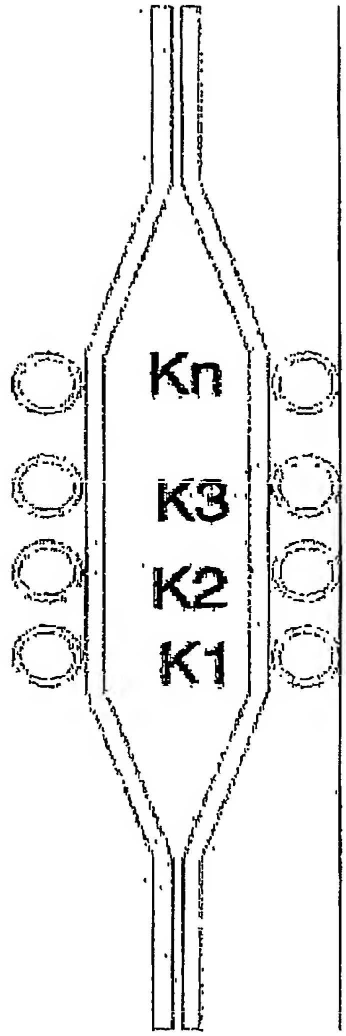

Fig. 14

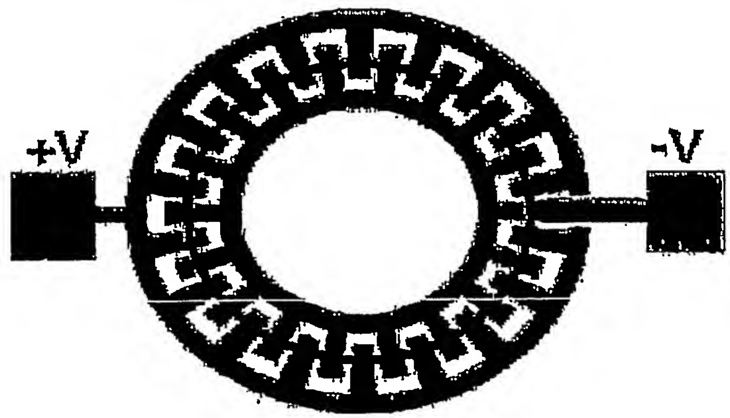

Fig 15.

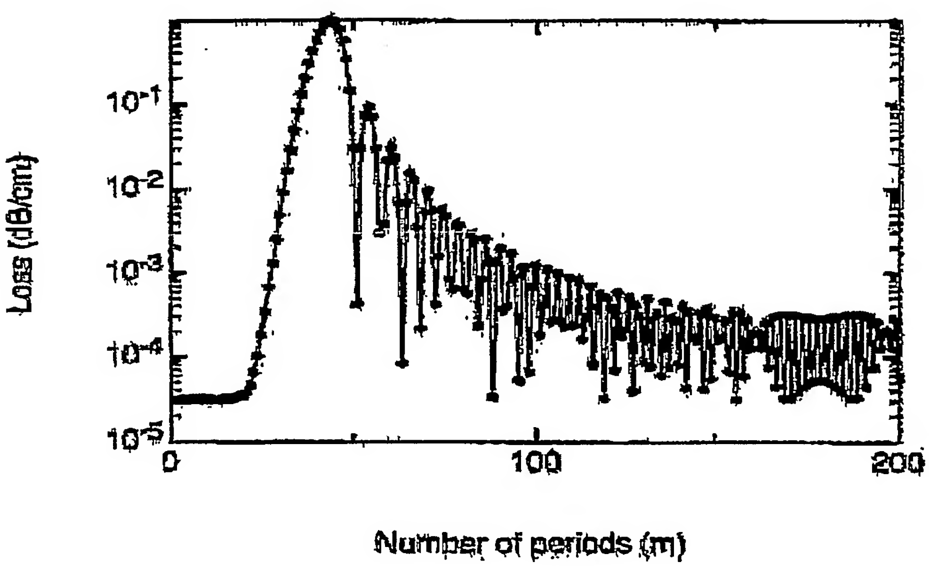

Fig. 16